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## Multi-Camera, High-Speed Imaging System for Kinematics Data Collection

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# **Multi-Camera, High-Speed Imaging System for Kinematics Data Collection**

## **INTRODUCTION**

This project was carried out to support the design of an unmanned underwater vehicle (UUV). In the field of UUV design and development it is becoming increasingly popular to use biological inspiration to design the propulsion and control mechanisms to achieve performance goals related to efficiency, stealth and maneuverability among others. Kellogg et al. (2003) have used insect wing flapping studies as inspiration for wing design. Ramamurti and Sandberg (2006) have used fish locomotion studies to optimize a fin design. Using the results of these studies, a biomimetic, active-deformation fin for underwater missions has been designed and built by Palmisano et al. (2007), and biomorphic flapping wing vehicles for aerial missions have been developed by Cylinder et al. (2005).

Using computational fluid dynamics (CFD) analysis, forces and moments created by the fins and wings are calculated over a number of cycles for a given set of kinematics. These force time-histories are analyzed to decide what fin or wing motion should be prescribed for various maneuvering capabilities. To match the forces produced in the CFD results, it is essential that the kinematics prescribed in these simulations be reproduced in the actual flapping appendage. While we can measure the forces and moments on the appendage directly using load and torque cells, knowing the actual kinematics allows us to easily correct the control inputs to achieve a better match of the desired kinematics. It also gives us the actual kinematics to input back into the CFD code to verify the accuracy of measured forces.

However, the kinematics of flapping motion is more difficult to obtain than for traditional propellers. Attempting to arrange a variety of sensors on the fins and wings would compromise the structural integrity of such lightweight mechanisms and would interfere with the flow fields around the flapping surfaces. Johansson and Lauder (2004) have demonstrated the capability of utilizing a multi-camera system to capture simultaneous high-speed images of moving appendages from two cameras. This system provides a non-invasive way to get the three-dimensional coordinates of the appendages throughout the stroke cycles. We have therefore chosen to pattern our facility after that in the Lauder Laboratory at Harvard University. Studying kinematics using this system in conjunction with CFD simulations is a novel approach to the verification of force production.

The processes and specifics of the camera system discussed in this paper are general and applicable to any test setup. However, the specific example of a fin design for use on a UUV is used to illustrate details.

## **FIN DESIGN AND TEST SETUP**

An actively deforming mechanical fin has been designed and built using compliant ribs by Palmisano et al. (2007). The fin is comprised of five ribs each actuated by a single servo-motor. The ribs are designed to bend in the desired shapes using compliant structure techniques. In addition to the actuation of each individual rib, the bulk rotation of the fin is controlled by a

servo-motor as well. The entire set of five ribs is encased in a liquid silicone rubber skin that is designed to elastically deform with the ribs while providing only a small resistance to the actuated motion. The nature of this fin with deforming ribs and skin precludes the use of encoders and other instruments used for direct kinematics data measurement that can be found on simpler rigid systems.

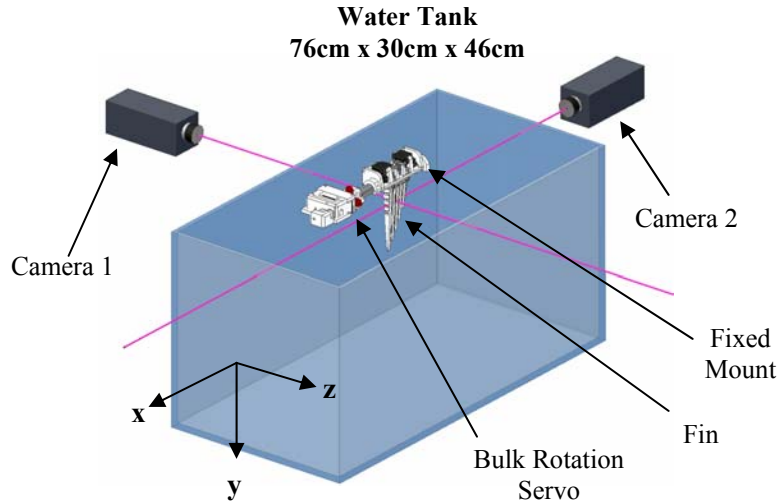


Fig. 1. Test Tank with Camera Setup (Palmisano et al., 2007)

A small water tank (76cm x 30cm x 46cm) is used to test the actuation of the fin. The fin and actuation mechanisms are suspended from a platform hanging above the test tank such that the fin is submerged in the water, Fig. 1. The test platform is also fitted with a load cell to measure the force produced along the x-axis and a torque cell to measure the moment around the x-axis, Fig. 2. Using the moment arm and kinematics data the forces along the y-axis and z-axis can be computed from this torque data as well.

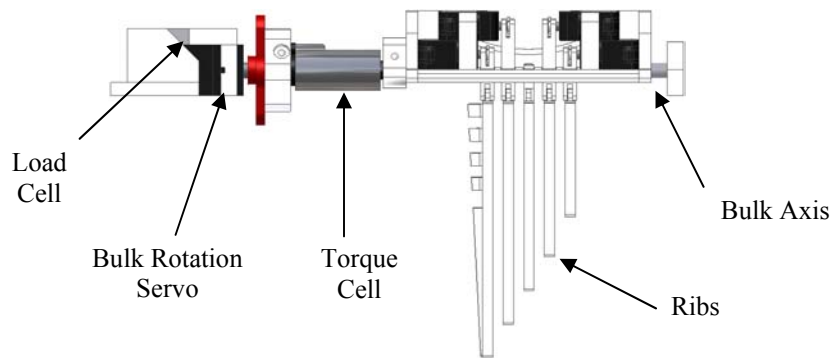


Fig. 2. Test Setup with Load and Torque Cells (Palmisano et al., 2007)

As a means of measuring the kinematics of the fin, two high-speed digital cameras from Canadian Photonic Labs (MS10K CCD, MS25K CMOS) are setup outside the tank to record images of the fin throughout its stroke. The cameras are positioned at  $\sim 90^\circ$  to each other, Fig. 1, to maximize the accuracy of the position measurements since this provides the most unique field

of view for each of the cameras. Each camera is connected to a computer through Ethernet cable to transmit recorded images to picture files stored on the computer's hard drive.

### CALIBRATION AND CAMERA COEFFICIENTS

The goal of the two-camera system is to convert two sets of two-dimensional (2-D) camera pixel coordinates into a single set of three-dimensional (3-D) inch coordinates without using background markers. To facilitate this, we must collect images of points with known 3-D location covering the space that the fin will operate. This can be done in a number of ways, but in the case of the fin test an easy method was devised by suspending a structure of LEGO bricks from a platform into the field of interest, Fig. 3. An image of the LEGO structure is taken from each of the two cameras and stored on the computer. Each point of interest on the structure must be identified in 2-D pixel coordinates from both cameras. Once a sufficient number of points to cover the desired space have been taken and recorded in 2-D pixel coordinates, the known 3-D inch coordinates of each of the points must be recorded as well. This provides the basis for a transformation from 2-D to 3-D coordinates.



Fig. 3. LEGO block calibration

Using the collected coordinates from the LEGO structure a direct linear transform written by Reinschmidt (1996) is implemented to find camera coefficients that define position and optical geometry for each camera separately. Direct linear transformation is a well established method for this conversion from 2-D digitized to 2-D image space coordinates. The method involves solving a set of simultaneous linear equations that yields the image space coordinates from the digitized coordinates (Woltring and Huiskes, 1990). The equations for each point,  $i$ , in matrix form are written as

$$\begin{bmatrix} X_i & Y_i & Z_i & 1 & 0 & 0 & 0 & 0 & -x_i X_i & -x_i Y_i & -x_i Z_i \\ 0 & 0 & 0 & 0 & X_i & Y_i & Z_i & 1 & -y_i X_i & -y_i Y_i & -y_i Z_i \end{bmatrix} \bar{a} = \begin{bmatrix} x_i \\ y_i \end{bmatrix}, \quad (1)$$

where  $[X_i \ Y_i \ Z_i]$  is the set of 3-D coordinates of the point,  $[x_i \ y_i]$  is the set of 2-D image coordinates of the point for the camera, and  $\bar{a}$  is the vector of camera coefficients.

## HIGH-SPEED IMAGING

Once the camera calibrations have been established we can take high-speed (up to 10,000 frames per second) images of the fin in motion. A camera speed of approximately 50 times the flapping frequency of the appendage is sufficient to capture the necessary kinematics features. For the fin, this value varies between 50-150 fps. It is essential that the two cameras take images from the same starting time and at the same sampling rate so there is a set of two images for each time step in the stroke of the fin. These synchronized images are used to establish the 3-D coordinates at each given time step.

To achieve a simultaneous starting time a triggering device is used to initiate the sampling of images from both cameras. The cameras are equipped with a trigger input to facilitate this operation. By sharing one trigger box and wiring the connection such that the same trigger signal is going to both cameras, Fig. 4, we can achieve a uniform starting time.



Fig. 4. Trigger Box and Connections

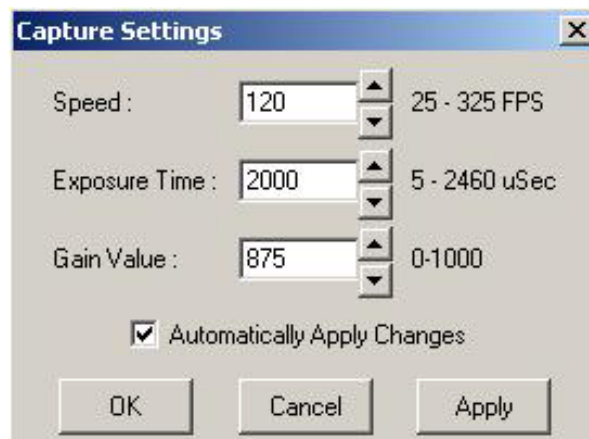


Fig. 5. Camera Capture Settings

Matching the sampling rates of the cameras involves setting them to the same values in their respective software programs, Fig. 5. This ensures that at every time step (as defined by the rate) there are two images to analyze. Other variables to consider in the software include the capture mode and image size for each camera. Capture mode must be set to ‘trigger’ rather than ‘continuous’ to make use of the trigger box. The image size for each camera should be set to the smallest size which captures the entire field of motion of the fin.

## IMAGE PROCESSING

With the camera coefficients and the series of time stamped images of the fin from each camera, we look at each set of images and record the points of interest. In this case, the points of interest are the five rib tips. Their locations in space and time throughout the stroke will tell us what the kinematics look like. A Matlab program called Digimat written by Madden (2004) is used to facilitate the collection of 2-D pixel coordinates from each camera and the transformation to 3-D inch coordinates. This program allows us to view two images side-by-side, and to input the matrix of camera coefficients that we have developed.

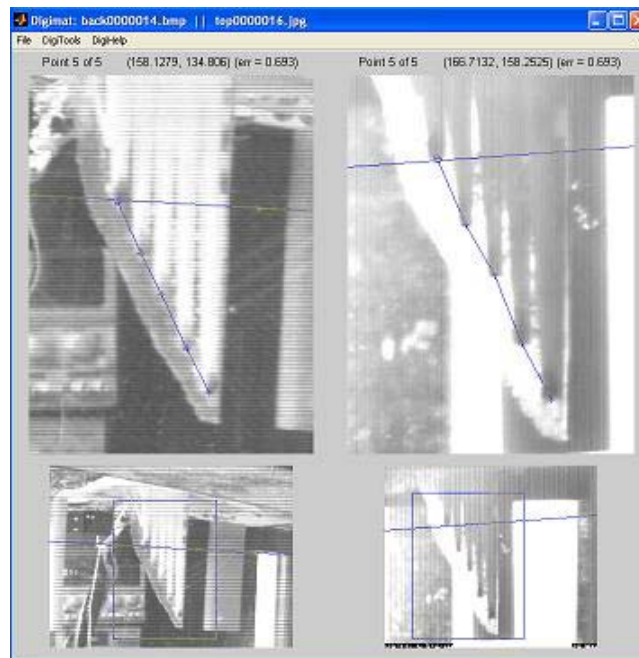


Fig. 6. Digimat GUI

The two side-by-side images (one from each camera) from the same time step are analyzed graphically using the mouse to click on the rib tips, Fig. 6. A helpful tool provided by Digimat is once a point on one of the images is recorded, a line appears on the other image to indicate the set of possible points that match with the chosen point based on the camera coefficients. Once a series of points from one image set is selected, the points are saved both as pixel coordinates for each camera and as 3-D inch coordinates. The conversion to 3-D inch coordinates is solved in Digimat using computations written by Reinschmidt (1996). The direct linear transformation for each camera is computed along with a least squares estimate to adjust for measurement and calibration errors (Woltring and Huiskes, 1990).

## POST PROCESSING

We need to know where the rib tips are in relation to a hinge axis to measure the rib rotation angles and compare them to the prescribed values. The hinge axis cannot be determined directly from the camera images for multiple reasons. The hinge axis is out of the water, while the fin is in the water for our experiments. This change of medium would invalidate the use of a single direct linear transformation because light travels differently through air and water. Also, the camera view of the hinge axis is blocked by a combination of wiring, liquid silicone rubber skin and the platform that holds the fin.

This inability to use video and perform a transformation into 3-D coordinates necessitates the use of a direct measurement of the hinge axis location. Once the location of the hinge axis is determined, defined as a line by the hinge point at rib 1 and the hinge point at rib 5, the entire set of rib tip and hinge points is rotated to ensure the hinge axis is parallel to the x-axis defined in the calibration. Then all of the points are translated to make the hinge point at rib 5 the (0,0,0) global point.

We also have the option of rotating the hinge axis to match a desired angle of attack or phase as determined by CFD results. Plots of the fin tip positions are created for comparison with prescribed kinematics, Fig. 7a. A wire-frame video that can be viewed from various angles is also created to visualize the fin operation in 3-D.

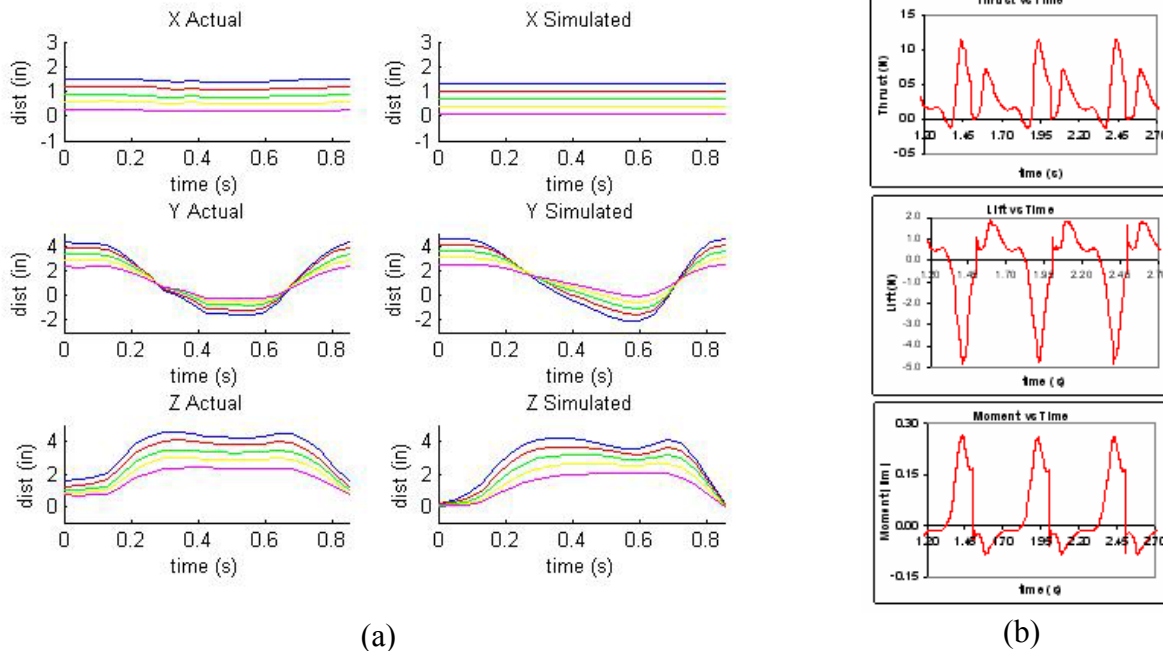


Fig. 7. Fin Kinematics and Force Production

(a) Experimental vs. Prescribed Kinematics (b) CFD Computed Force and Moment Production

The results of the kinematics time-histories are used to prescribe the motion of a fin in CFD simulations that is identical to the experimental fin in shape and size. Running the simulation using *feflo*, an incompressible flow solver created by Ramamurti et al. (1999), the forces and moments produced by the fin are computed, Fig 7b.

We have iterated our actuator input values to the actual fin servo-motors based on the results of the image digitizing and analysis. These iterations have allowed the fin to become more efficient at producing the greater thrust forces through improvement of the rib kinematics throughout the stroke. The success of changing inputs to the fin based on discrepancies between desired and actual kinematics validates the need for a multi-camera system.

### ADAPTABILITY

The cameras' locations and viewing areas can be easily adjusted using a system of extruded aluminum bars and connectors, Fig. 8, in conjunction with interchangeable lenses to accommodate a variety of test fins and wings. A new calibration must be made whenever the cameras are moved to a new location. Camera settings including image size and capture speed must also be adjusted for different fin and wing sizes, and flapping speeds.



Fig. 8. Camera Slide System

A series of BITE-wing vehicles that were designed and built by Cylinder et al. (2005) have been tested using the multi-camera, high-speed system. Markers must be placed on the fins, Fig. 9a, to allow measurement of the surface curvature time-history, which is essential for accurate computation of the interactions of the downstream wing pair with the time-varying vorticity shed from the pair of upstream flapping surfaces, Fig. 9b. The advantages of the two-camera system for kinematics data collection from the BITE-wing vehicles are similar to those for the actively deforming fin. Each of the four wings on the BITE vehicles is affected by aerodynamic forces causing it to deform in ways that cannot be measured by onboard sensors due to inaccuracy and

weight concerns. The measured kinematics data is essential for computation of the unsteady force and moment time-histories produced by the wings (Ramamurti et al. 2005).

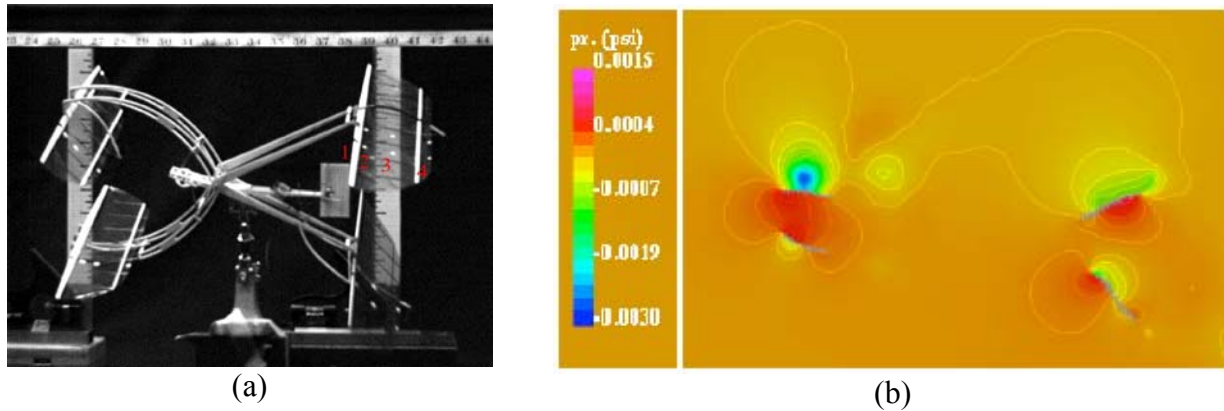


Fig. 9. BITE Vehicle (a) BITE showing markers used for kinematics measurement (b) Pressure contours on the symmetry plane (Ramamurti et al. 2005)

## CONCLUSION

Multi-camera image processing has proven an essential tool for verifying force production results and accuracy of flapping appendage vehicles. Three-dimensional points on the fin or wing are determined from the intersecting points in the image spaces of two cameras using direct linear transformations. This system provides a non-invasive method of kinematics data collection which is essential for lightweight vehicles and high frequency flapping. Iteration based on this data in connection with CFD simulation results is a novel approach to flapping actuation design and is important for improvement of fin or wing performance.

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